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QUANTITATIVE VERIFICATION OF THE HYDROGEOLOGICAL MODEL OF THE MOFETE GEOTHERMAL FIELD, CAMPANIA, ITALY

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ABSTRACT

The purpose of this study was to verify quantitatively and to refine the conceptual hydrogeological model of the Mofete Geothermal field near Naples, Italy, using a numerical simulator. A three-dimensional, two-phase numerical simulation model of the reservoir was developed based on the conceptual model and the interpretation of the long-term interference test data. The measured temperature distribution was matched, by trial and error, with the temperature distribution calculated by the model after a simulated geological time, without any production, thus validating the conceptual model. The locations and extent of recharge and discharge and the permeability distribution were the main fitting parameters. The numerical modeling of the initial state helped refine the conceptual model by indicating that: (a) there is very little communication between the layers; (b) fluid flows from NE to S through the system in the 275 to 850 m level; and (c) the heat source underneath the field is of a limited areal extent.

INTRODUCTION

The Mofete field is part of the large Phlegrean fields caldera, located west of Naples in southern Italy (Figure 1). The Phlegrean caldera has a diameter of 15 km, with its southern part lying underwater at the Gulf of Pozzuoli. The northern part of the caldera has been substantially modified by successive volcanic and tectonic activity.

Attracted by hydrothermal activity at the bottom of the Gulf of Pozzuoli and inshore at the Solfatara, Agnano and Mofete areas, an unsuccessful geothermal exploration program was carried out from 1939 to 1954. This exploration identified a shallow geothermal reservoir up to a depth of 500 - 900 m. In 1978 an intensive exploration and drilling program in the Mofete area was resumed by AGIP, S. p. A. Figure 2 shows the locations of the development wells. Drilling of deep wells during this latest effort discovered two additional high temperature water dominated reservoirs at approximately 1300 and 2700 m depths (Carella and Guglielminetti, 1983). Figure 3 shows the temperature profiles measured in a typical deep well at Mofete. The deepest reservoir, discovered in well Mofete-5, is highly saline [150,000 parts per million (ppm) of total dissolved solids (TDS) at the reservoir condition of 347°C]. The middle reservoir, discovered by well Mofete-2, apparently occurs in a formation of fractured volcano-sedimentary rocks. Reservoir liquid temperature is 337°C and salinity is 18,200 ppm. The shallow, previously known reservoir which is also the most productive, is located at a depth of 500 to 900 m and occurs in a section of mainly fractured volcanic rocks. The salinity of the water in the shallow reservoir is 30,000 ppm and the temperature is 247°C. Wells 1, 3D, 7D, 8D and 9D are completed in this shallow reservoir, known as the Mofete-1 reservoir.

The waters of the Phlegrean fields caldera, according to geochemical analysis, are a mixture of local meteoric waters and deep hot waters of marine origin locally, the water chemistry is affected by steam loss.

The purpose of this study was to verify quantitatively and to refine the conceptual hydrogeological model of this field by numerical simulation of its initial state.

WELL TEST DATA ANALYSIS

From April to August, 1985 an interference test was carried out in the Mofete field. The production well during the test was MF-1, while wells MF-2, MF-8D and MF-9D were used as observation wells. The fluid produced was injected into well MF-7D. The downhole pressure versus time from the observation wells, downhole pressure and total flow rate versus time from the production well, and injection flow rate versus time data are presented in Figure 4.

Figure 4 shows that well MF-2 is not reacting to the active well MF-1. This observation agrees with the inference from geochemical data that the two reservoirs (Mofete-1 and Mofete-2 reservoirs) are independent (MF-2 is completed in the Mofete-2 reservoir while the active well is in the Mofete-1 reservoir). The measured response in the other two observation wells, MF-8D and MF-9D, completed in the same reservoir (Mofete-1) as the active well MF-1, showed a clear response to the active well.

An analytical simulator for multi-rate pressure interference tests was used to match the measured pressure responses in the observation wells to the calculated responses, using reservoir flow capacity and the storage capacity for matching calculated with observed data. Flow capacity, as defined here, is the product of permeability and net fractured thickness; storage capacity is defined as the product of porosity, net fractured thickness and total rock/fluid compressibility. The best match to the measured pressure response in observation well MF-8D was achieved with a flow capacity of 11,200 md•m and a storage capacity of 0.24 m/bar (Figure 5). The best match to the measured pressure response in observation well MF-9D was achieved with a flow capacity of 10,250 md•m and a storage capacity of 0.34 m/bar (Figure 6). These values of reservoir flow and storage capacities were useful in constructing the numerical model of the field as described below.

SIMULATION PROCEDURE

Numerical simulation was conducted employing a three-dimensional integrated finite-difference numerical simulator capable of handling the coupled non-isothermal transport of water, steam, gas and heat (by conduction and convection) in porous and fractured media.

Figure 7 summarizes the procedure used for initial-state modeling in this study. The process began with the AGIP's conceptual hydrogeological model, refined by analyses of the well test data. After a careful consideration of the refined model, a grid was generated to discretize the geothermal system in 3 dimensions. The grid was delineated on the basis of the following constraints:

1. the need to define an individual grid block for each known zone of fluid discharge or recharge and/or well location to be used later in exploitation modeling;
2. topography;
3. location of faults or aquifers controlling convection;
4. lithologic variations only where it causes a significant variation in any hydrologic property (porosity, permeability, etc.) or thermal property (thermal conductivity, specific heat, etc.);
5. the need to control "numerical smearing", particularly in the calculated vertical temperature distribution, which is the most reliable and extensive observed subsurface information available to this study; and
6. the philosophy that the parts of the system with more information should have a finer grid network than those with less.

The next step was to estimate (from observed or inferred data) all relevant parameters for each grid block. If no observed or inferred data were available to estimate a parameter, a value of the parameter was assumed based on our knowledge of similar systems. The parameters to be quantified for each grid block were:

1. volume,
2. area of contact and nodal distance between the grid block and adjoining ones,
3. elevation,
4. porosity,
5. permeability in 3 perpendicular directions,
6. density of the rock matrix,
7. thermal conductivity of the rock matrix,
8. specific heat of the rock matrix,
9. compressibility of the rock matrix,
10. water/steam relative permeability characteristics,
11. water/steam capillary pressure characteristics (capillary pressure was assumed to be zero)
12. temperature,
13. pressure,
14. steam saturation, and
15. gas content (gas content was assumed to be zero).

It should be noted that in initial-state modeling, the main goal is to verify the temperature distribution and heat discharge aspects of the model. In this context, the rock properties of importance are permeability and thermal conductivity. Unlike in exploitation modeling, porosity, density and specific heat of the rock are not important parameters for initial-state modeling. Therefore in initial-state modeling it suffices to use average values of porosity, density and specific heat of the rock, but more detailed distributions need to be specified for permeability and thermal conductivity of the rock.

For the blocks with discharge or recharge of fluid, the rate of recharge or discharge was specified. For boundary blocks, one of the following hydraulic boundary conditions was specified: a) a boundary with a given rate of recharge (or discharge); b) a boundary at a constant pressure, or c) a no-flow boundary. The thermal boundary condition was usually assumed to be one of constant temperature.

The above data were input, and the model was allowed to run for a simulated geological time of several thousand years. The simulation time was increased until the system evolved to a quasisteady state. If the system failed to reach a quasisteady state in many tens of thousands of years, the discretized system was considered unrealistic and the input parameters were modified suitably.

Once the system reached a quasisteady state in a reasonable geological time span (a few tens of thousand years), the final distributions of temperature and pressure, as computed by the model, were compared to the observed (or inferred) distributions. If the calculated and observed (or inferred) distributions matched within a chosen tolerance, the model was assumed to be a representative quantitative model of the initial state of the system. If not, the input parameters were modified further and, by numerous iterations, a match was obtained between the observed and calculated distributions of temperature and mass and heat discharge. If no reasonable set of input parameters provided such a match, the model was considered erroneous and revised accordingly. If the system did not reach a quasisteady state within a reasonable geologic time span, the model was assumed to be set up incorrectly; and appropriate modifications were made.

DESCRIPTION OF THE SIMULATION MODEL

The simulation model chosen for the Mofete field was oriented in a NW-SE direction, approximately centered at the existing wellfield (Figure 2). The model covers a square area of 25 km^2 extent. In the vertical dimension, the model extends from the topographic surface at 0 m msl (mean sea level) to -3,000 m msl. This 3,000 m thickness is subdivided into 5 layers of thicknesses 275, 575, 500, 610 and 1040 m from top to bottom. The subdivision was done with regard to the lithological cross sections of the field. An additional layer in contact with the bottom of the model containing the heat source was used as a boundary layer. The assigned volume to this bottom boundary layer was large enough to prevent any variation of its initial conditions in the simulated geological time required by initial-state simulation. This pattern of gridding resulted in a total of 140 elements; of these 140 elements 19 were used as boundary blocks including the boundary created by the atmosphere at the top of the model. The grid blocks in each of the top 5 layers are shown in Figures 8 through 12.

Five major rock types are represented in the model, one for each layer: a) layer 1 - yellow tuff; b) layer 2 - Chaotic tuffites; c) layer 3 - latitic lavas; d) layer 4 - tuff and tuffites; e) layer 5 - lavas. In some cases it was necessary to subdivide the major rock units into subclasses to account for variations in rock properties, especially permeability. The values of density, porosity and specific heat for each rock type, when unknown, were set to typical values for geothermal systems of similar characteristics and are presented in Table 1 (at the end of this paper). However, initial-state modeling is not very sensitive to these parameters, the model results being controlled mainly by the permeability distribution.

The boundary conditions at the earth's surface are those of a heat sink (the atmosphere) at constant pressure (0.1 MPa.a) and constant temperature (20° C). All other boundary conditions were taken to have constant pressure and constant temperature. For the initial state modeling, no production from wells was considered. In order to reproduce the inferred temperature distribution based on AGIP's geological interpretation of the field, a sink and a source had to be located in layer 2, both with a mass flow rate of 1 kg/s (Figure 9).

RESULTS OF INITIAL-STATE SIMULATION

Numerous runs, using different permeabilities of the basic rock types, were necessary to obtain a reasonable match between the calculated temperatures and temperatures derived from AGIP's conceptual hydrogeological interpretation of Mofete.

Figures 8 to 12 show the calculated temperatures and temperature contours inferred from the measured temperature data. The calculated temperatures shown in those figures correspond to the temperature at the center of each block. The agreement between the calculated and measured temperatures is quite good.

Although no natural discharge data were available, the temperature contours derived from AGIP's geological interpretation show an elongation of the temperature anomaly towards the south of the field up to 1,350 m msl. Therefore, a sink and a source were added in the second layer of the simulation model to simulate convection, and the southward distortion in the temperature anomaly. The location of the recharge was moved from place to place in the different trial runs, and the location shown in Figure 9 was judged the most likely. The mass flow rate of 1 kg/s gave the best match. According to these results from the simulation, the flow in the Mofete-1 reservoir is likely to occur from NE to S.

In order to reach a reasonable match between the observed and calculated temperature distributions, the vertical permeability in general was kept low (as can be seen from Table 1), which suggest little to no communication between layers.

Initially, the heat source at the bottom boundary layer was considered to be in contact with layer 5 at all points but after several runs without success in matching the temperatures in the lower layers, it was decided to reduce its contact area which led to a better match. This suggests a localized heat source rather than a widespread source.

In general terms the results of the simulation validated the conceptual hydrogeological model of AGIP; since it was possible to obtain a reasonable match between the measured and calculated temperature distributions using the geological features suggested by the conceptual model.

CONCLUSIONS

Numerical simulation of the initial state of the Mofete field validated the conceptual hydrogeological model, and refined the conceptual model by indicating that:

1. there is little to no communication between layers;
2. the flow of fluids in the Mofete-1 reservoir is occurring from NE to S; and
3. the heat source underneath the Mofete field is of a limited areal extent.

ACKNOWLEDGEMENT

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Table 1. Mofete Three Dimensional Simulation - Rock Properties

Major Rock Type	Rock Type Sub-Class	Density (kg/m³)	Porosity	Permeabilities (m²)* 1	2	3	Thermal Conductivity (J/m.s.°C)	Rock Specific Heat (J/kg°C)
Yellow Tuff	1	2600.	.05	1.E-15	1.E-15	1.E-17	2.50	1000.
	2	2600.	.05	1.E-13	1.E-13	1.E-16	2.50	1000.
	3	2600.	.01	1.E-18	1.E-18	1.E-18	2.50	1000.
	4	2600.	.05	2.E-14	2.E-14	1.E-16	2.50	1000.
	5	2600.	.05	4.E-14	4.E-14	1.E-16	2.50	1000.
Chaotic Tuffites	1	2600.	.138	0.3E-15	0.3E-15	1.0E-16	2.50	1000.
	2	2600.	.138	6.E-14	6.E-14	1.E-14	2.50	1000.
	3	2600.	.138	3.E-15	3.E-15	5.E-16	2.50	1000.
	4	2600.	.138	5.E-15	5.E-15	1.E-15	2.50	1000.
Latitic Lavas	1	2600.	.138	0.7E-16	0.7E-16	0.5E-16	2.50	1000.
	2	2600.	.138	3.E-15	3.0E-15	0.5E-16	2.50	1000.
	3	2600.	.138	0.7E-16	0.7E-16	0.1E-16	2.50	1000.
	4	2600.	.138	5.0E-15	5.0E-15	5.0E-15	2.50	1000.
Tuffs & Tuffites	1	2600.	.144	4.6E-16	4.6E-16	4.6E-16	2.50	1000.
	2	2600.	.144	4.6E-14	4.6E-14	8.0E-14	2.50	1000.
	3	2600.	.144	3.5E-14	3.5E-14	3.5E-14	2.50	1000.
Lavas	1	2600.	.138	4.1E-16	4.1E-16	4.1E-16	2.50	1000.
	2	2600.	.138	4.1E-14	4.1E-14	4.1E-14	2.50	1000.

* 1 Horizontal permeability (SW-NE)
2 Horizontal permeability (NW-SE)
3 Vertical permeability

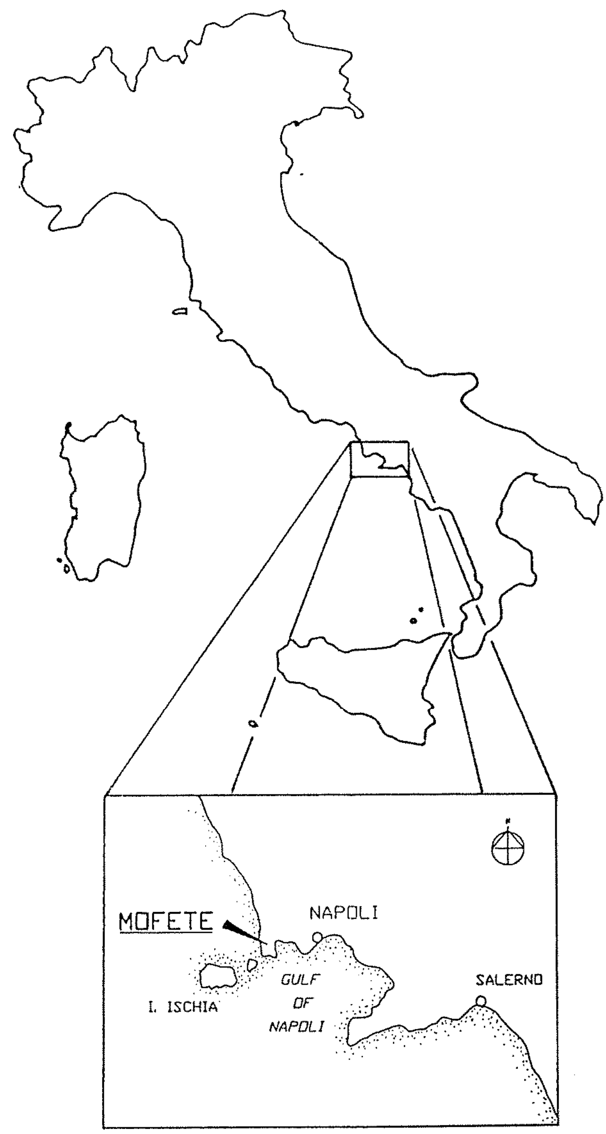

Figure 1: Location of the Mofete field in Italy

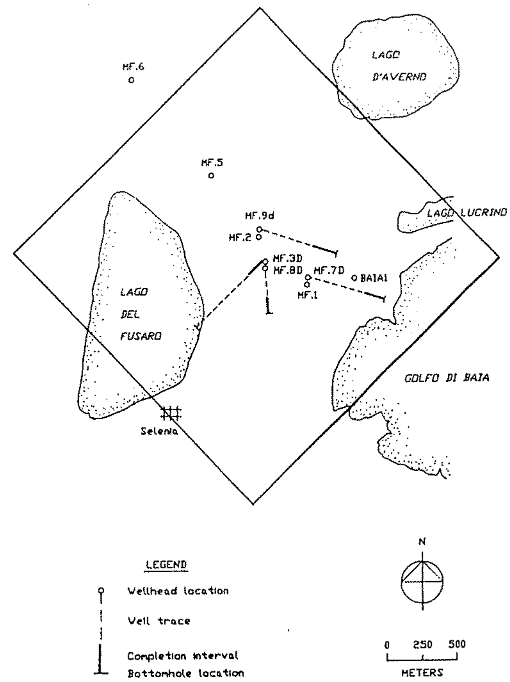

Figure 2: Area considered for three-dimensional reservoir simulation

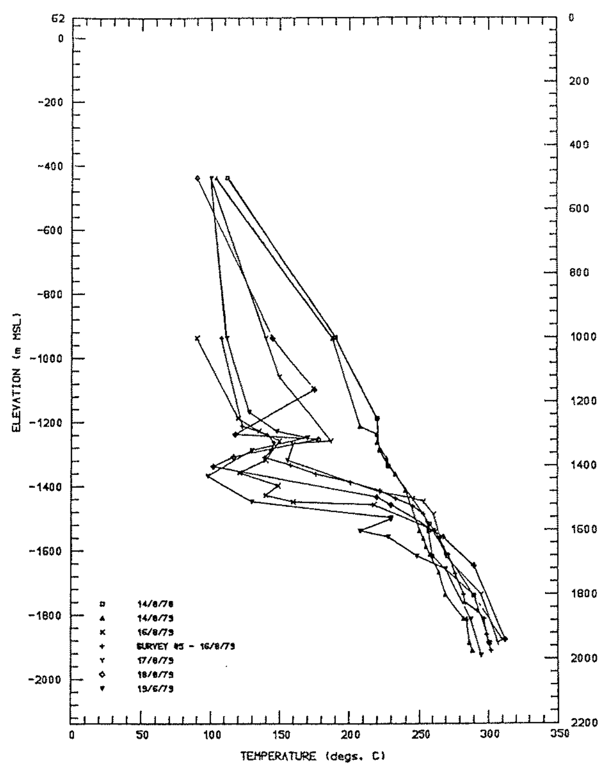

Figure 3: Temperature profiles, well MF−2

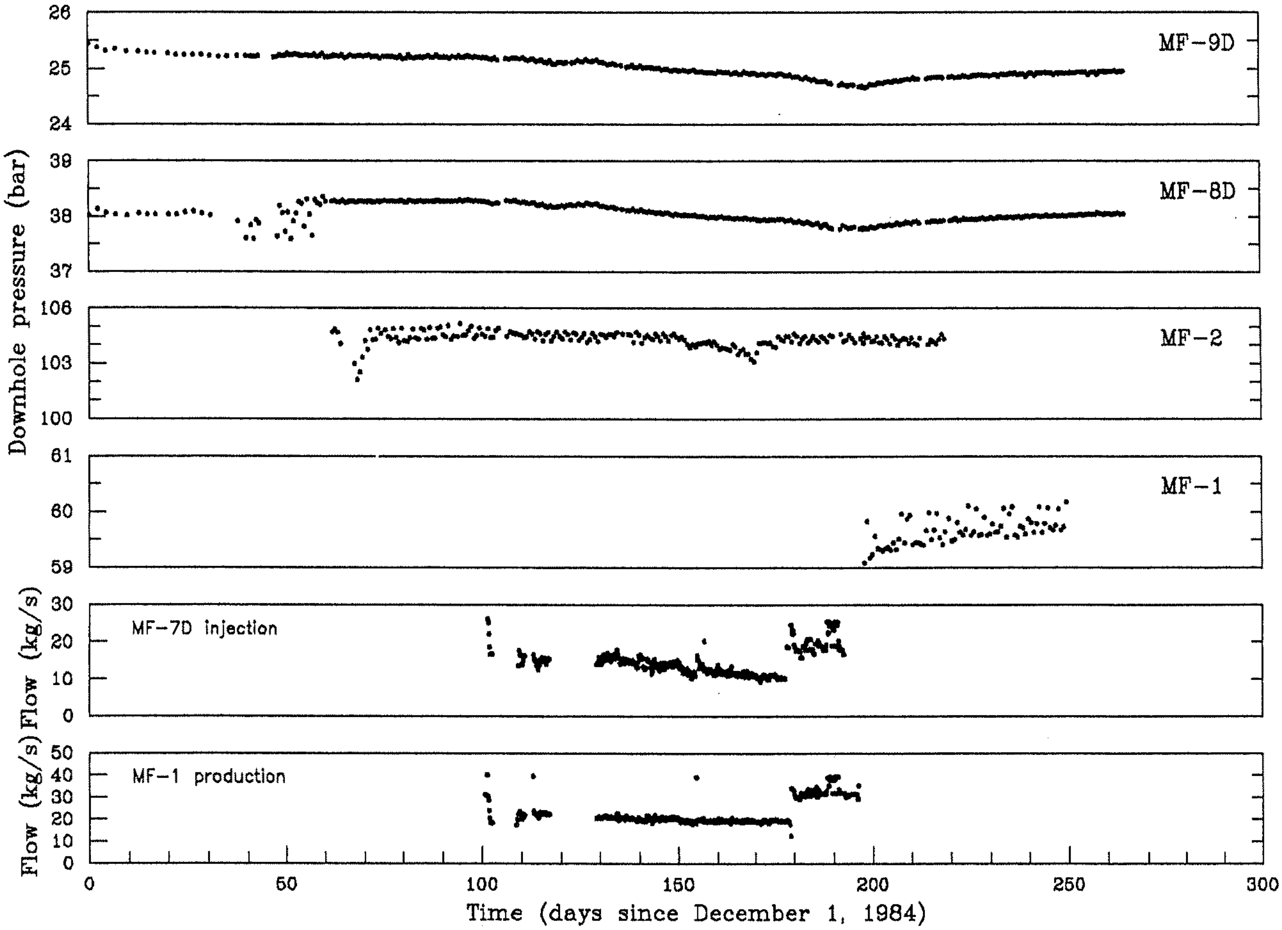

Figure 4: Flow rate and pressure data measured during interference test

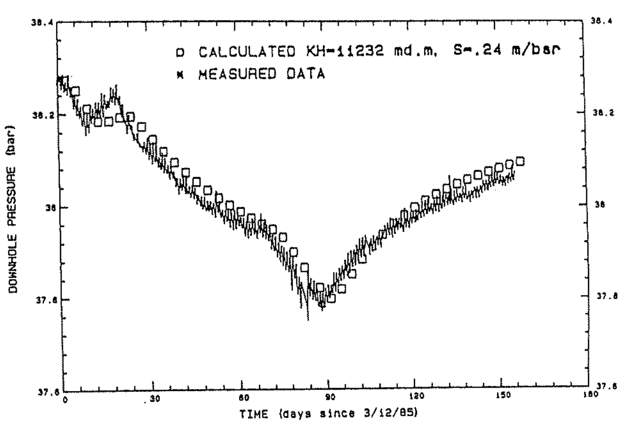

Figure 5: Measured and calculated pressure vs time, well MF-8D

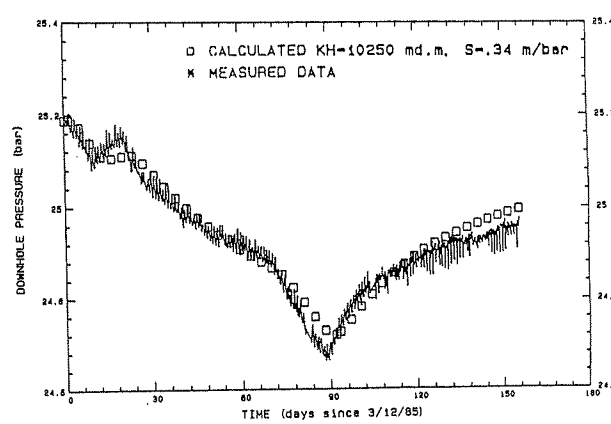

Figure 6: Measured and calculated pressure vs time, well MF-9D

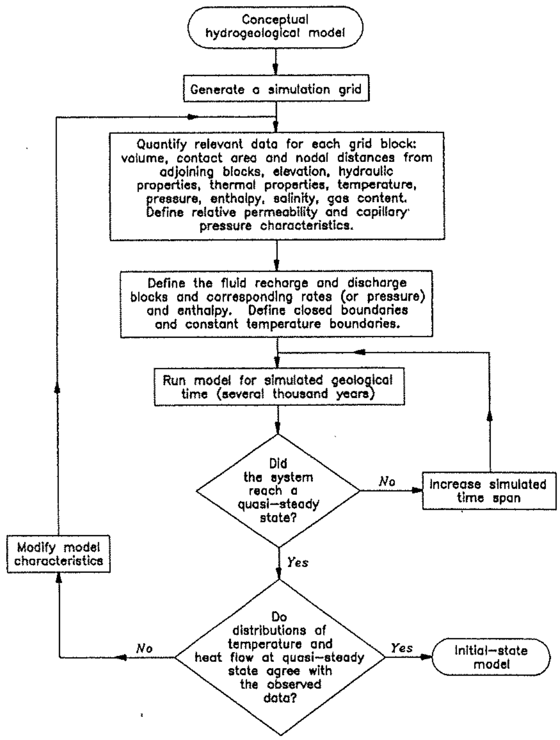

Figure 7: Flow chart of numerical simulation of the initial-state.

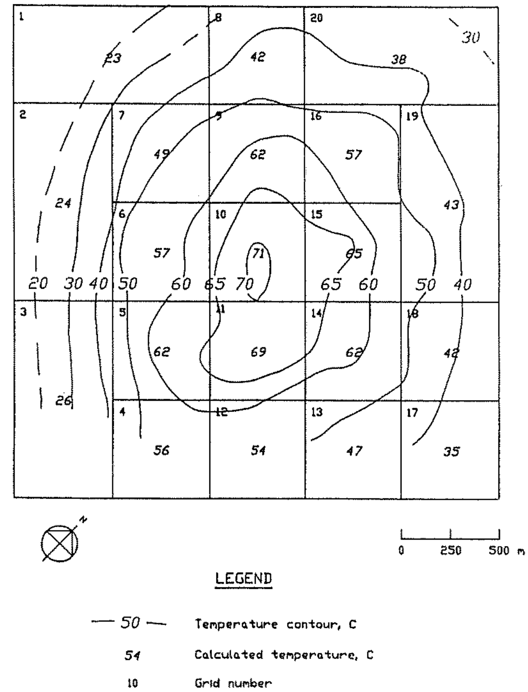

Figure 8: Calculated temperatures and inferred temperature contours, layer 1 (0–275 m)

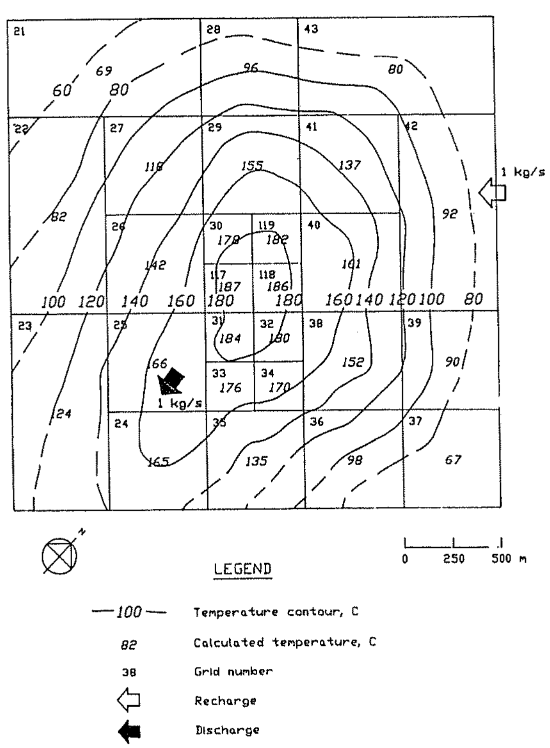

Figure 9: Calculated temperatures and inferred temperature contours, layer 2 (275–850 m)

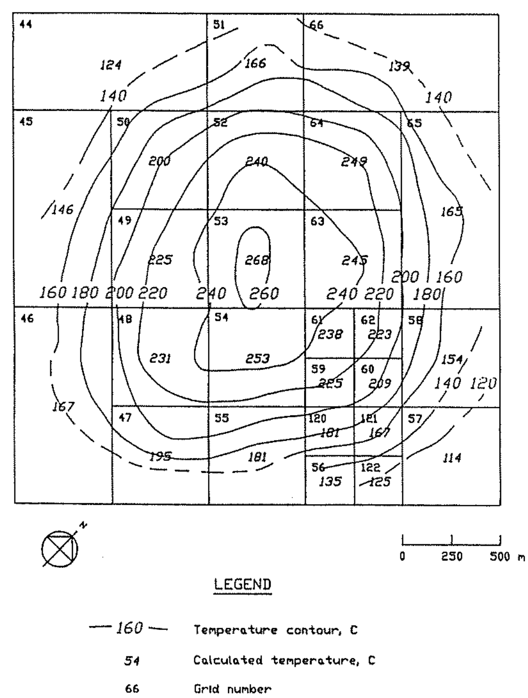

Figure 10: Calculated temperatures and inferred temperature contours, layer 3 (850–1350 m)

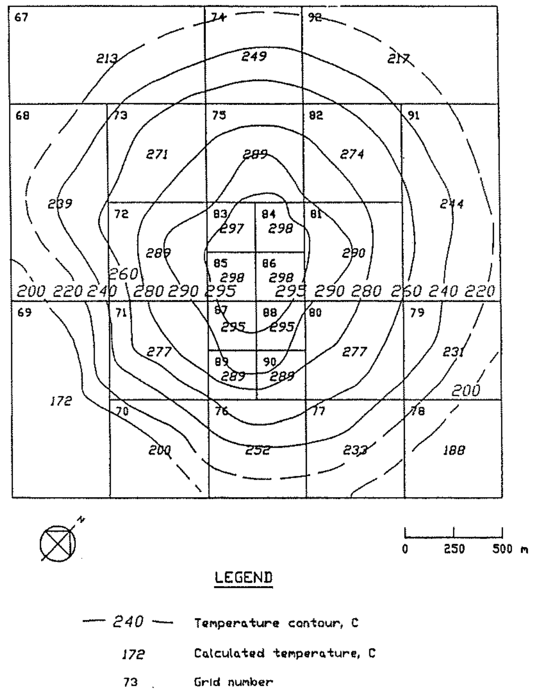

Figure 11: Calculated temperatures and inferred temperature contours, layer 4 (1350–1960 m)

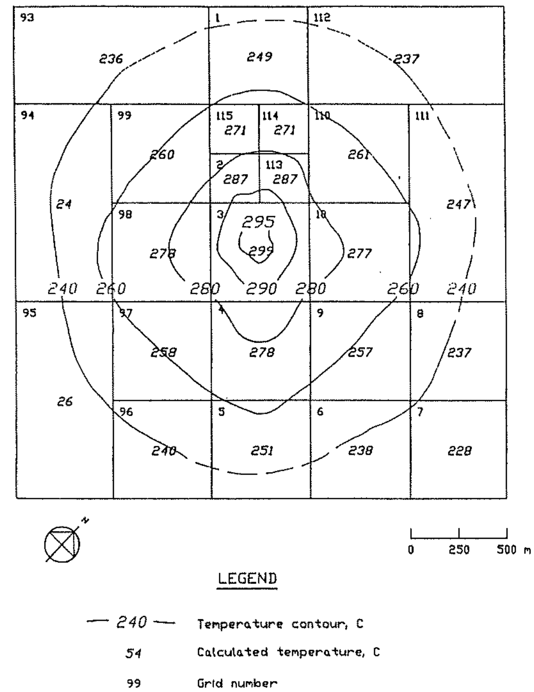

Figure 12: Calculated temperatures and inferred temperature contours, layer 5 (1960–3000 m)